

This Page Is Inserted by IFW Operations
and is not a part of the Official Record

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images may include (but are not limited to):

- BLACK BORDERS
- TEXT CUT OFF AT TOP, BOTTOM OR SIDES
- FADED TEXT
- ILLEGIBLE TEXT
- SKEWED/SLANTED IMAGES
- COLORED PHOTOS
- BLACK OR VERY BLACK AND WHITE DARK PHOTOS
- GRAY SCALE DOCUMENTS

IMAGES ARE BEST AVAILABLE COPY.

**As rescanning documents *will not* correct images,
please do not report the images to the
Image Problem Mailbox.**

FIELD OF INVENTION

[0001] The present invention relates to manufacturing small electro-mechanical devices, and more particularly, to bonding and packaging of members of Micro-Electro-Mechanical Systems (MEMS) and MEMS based products using a Solid-Liquid InterDiffusion (SLID) bonding process.

BACKGROUND OF INVENTION

[0002] Micromechanics, micro-machines, or more commonly, Micro-Electro-Mechanical Systems (MEMS) are an integration of mechanical elements, such as sensors and actuators, and/or electronics on a common substrate through the utilization of micro-fabrication technology. MEMS range in size from a few microns to a few millimeters. While the electronics are fabricated using Integrated Circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes), micro-mechanical components are fabricated using compatible "micro-machining" processes that selectively etch away parts of a silicon wafer or add new structural layers to form mechanical and electromechanical devices.

[0003] MEMS bring together silicon-based microelectronics with micro-machining technology, thereby making possible the realization of a complete system-on-a-chip. MEMS augment the computational ability of microelectronics with the perception and control capabilities of microsensors and/or microactuators. Examples of such electrical and mechanical combinations are gyroscopes, accelerometers, micromotors, and sensors of micrometric size, all of which may need to be left free to move after encapsulation and packaging. MEMS may be used within digital to analog converters, air bag sensors, logic, memory, microcontrollers, and

video controllers. Example applications of MEMS are military electronics, commercial electronics, automotive electronics, and telecommunications.

[0004] In the fabrication of MEMS and other microstructures, two substrates or components

5 may be structurally integrated together, such as by structural bonding. The structural bonds can be provided by any of several bonding techniques known in the art. For example, a direct bond may be formed by joining two clean, polished surfaces together under compressive force.

Alternatively, two adjacent solder structures may be integrated and bonded together by reflowing the solder at an elevated temperature. In addition, an anodic bond may be formed between an

10 insulating substrate and a conducting or semi-conducting substrate by the application of a high voltage, such as 1,000 volts, across a junction at an elevated temperature. Structural bonds, such as the aforementioned, are well developed for providing mechanical integration of two or more microstructures. However, a structural bond's strength may not be effective under harsh conditions. Additionally, these structural bonding methods are each application specific bonding methods and they also may not be viable methods for bonding within a fragile device such as a 15 MEMS.

[0005] In some microstructure and MEMS applications, a pressure seal may be desired, such as to isolate a cavity internal to a MEMS or other microstructure from the surrounding

20 environment. Pressure seals may be required, for instance, when a high-pressure gas atmosphere is desired inside a cavity, such as for example, to increase a breakdown voltage threshold used within an electrical component of a MEMS. In other applications, an evacuated cavity may be required, such as for example, for improving a thermal isolation of suspended radiation detectors in a microbolometer. Unfortunately, common structural bonding techniques are generally

inadequate to provide pressure sealing because of surface variations and imperfections that preclude the formation of a tight seal across the full extent of a structural bond.

[0006] In the packaging of MEMS devices, protection is an important element because corrosion, moisture and debris can prevent the devices from working. Each device should be hermetically sealed, allowing only a negligible amount of gas to be exchanged between the passages in the MEMS body and the atmosphere during the life of the MEMS, in order to prevent the device from becoming contaminated. Existing packaging of MEMS devices typically involve selecting an appropriate arrangement of the MEMS device within a system, selecting an appropriate material for use in bonding the MEMS device in the system, and selecting an appropriate process for applying the material to create a bond. These packaging solutions often involve redesigning a MEMS layout due to materials and processes used, and therefore, are burdensome to accomplish. For example, in a Leadless Ceramic Chip Carrier (LCCC) package, a lid may be soldered to seal the package. However, outgassing may occur when soldering which requires the use of getters to alleviate the outgassing. This results in additional materials, processes, time, and costs.

[0007] MEMS packaging presents challenges compared to IC packaging due to the diversity of MEMS devices and the requirement that many of these devices are in continuous and intimate contact with their environment. Presently, nearly all MEMS development efforts must develop a new and specialized package each time a new device is designed. Application specific packaging is not an efficient method of sealing MEMS based products. Consequently, most manufacturers find that packaging is the single most expensive and time-consuming task in a MEMS product development program. Such packaging as wafer level protected MEMS, capped

MEMS, and several other types of molded packages have been used by manufacturers. All of these options can be realized in System in Package (SiP) solutions that combine multiple chips and passive devices into one device. These SiP solutions are aimed at reducing the cost of MEMS packaging and providing standardization solutions, however these packaging options

5 may increase the costs of MEMS due to additional design efforts, and since each device requires a specific package, it is believed that the standardization of MEMS packaging can not be realized using known techniques.

[0008] One of skill in the art would appreciate a bonding and packaging process that is capable of handling a mass production of MEMS. It would also be desirable to provide a simple process for bonding and packaging MEMS devices to enable design and manufacturing to be completed in a timely fashion and at a low cost.

[0009] It would also be desirable to provide a low temperature process for the bonding and packaging of MEMS devices that yields a high temperature and high strength bond. In addition, a selective temperature process for bonding may be desired using materials having different properties such as compositions and melting temperatures.

[0010] It would also be desirable to provide a single bonding process for bonding components to MEMS devices and for packaging the MEMS devices in order to simplify the manufacturing process of MEMS devices. For example, a uniform bonding and packaging method is desired for use in approximately all bonds present in a MEMS device.

SUMMARY OF THE INVENTION

[0011] In view of the above, a method of forming a bond between mating surfaces of members of a Micro-Electro-Mechanical System (MEMS) is provided. The method comprises depositing a first layer of material on a first mating surface. The first layer of material is selected from the group consisting of gold and tin. For example, a material selected from Groups 11 or 14 of the periodic table of elements may be a suitable material with desired properties for bonding. A second layer of material is deposited on a second mating surface. The second layer of material is selected from the group consisting of indium and lead. The first mating surface is pressed against the second mating surface, thereby pressing the first layer of material to the second layer of material. An alloy is formed between the mating surfaces serving as the bond between the first mating surface and the second mating surface of the members of the MEMS.

10
9
8
7
6
5
4
3
2
1

20

[0012] In another embodiment, a Micro-Electro-Mechanical System (MEMS) is provided including a substrate, a micro-machine coupled to the substrate and a cover coupled to the substrate. The cover and the micro-machine are coupled to the substrate by forming at least one bond between mating surfaces of the cover and the substrate and between mating surfaces of the micro-machine and the substrate. The at least one bond is formed by depositing a first layer of material on a first mating surface. The first layer of material is selected from the group consisting of gold and tin. A second layer of material is deposited on a second mating surface. The second layer of material is selected from the group consisting of indium and lead. The first layer of material is pressed against the second layer of material, thereby forming an alloy to serve as the bond between the first mating surface and the second mating surface of the cover and the substrate and between the first mating surface and the second mating surface of the micro-machine and the substrate.

[0013] These as well as other features and advantages of the present invention will become apparent to those of ordinary skill in the art by reading the following detailed description, with appropriate reference to the accompanying drawings.

BRIEF DESCRIPTION OF FIGURES

[0014] Presently preferred embodiments of the invention are described below in conjunction with the appended drawing figures, wherein like reference numerals refer to like elements in the various figures, and wherein:

5 [0015] FIGURE 1A is a side view of an illustration of packaging employed in accordance with one embodiment of the present invention;

10 [0016] FIGURE 1B is an expanded view of FIGURE 1A illustrating bonds arranged in accordance with one embodiment of the present invention;

15 [0017] FIGURE 2A is a cut open top view of FIGURE 1A;

20 [0018] FIGURE 2B is an expanded view of FIGURE 2A illustrating bonds arranged in accordance with one embodiment of the present invention;

25 [0019] FIGURES 3A-3C are conceptual process diagrams showing various stages of a method of processing a surface according to one embodiment of the present invention;

[0020] FIGURES 4A-4C are conceptual process diagrams showing various stages of a method of processing another surface according to one embodiment of the present invention;

[0021] FIGURE 5A illustrates a conceptual processing step employed in one embodiment of the present invention;

[0022] FIGURE 5B illustrates a conceptual final bond created in accordance with one embodiment of the present invention;

[0023] FIGURES 6A-6B conceptually illustrate the processing step of FIGURE 5A;

[0024] FIGURE 7A conceptually illustrates individual atoms of FIGURE 6A;

5

[0025] FIGURE 7B conceptually illustrates individual atoms of FIGURE 6B;

[0026] FIGURES 8A-8B illustrate amounts of concentrations present according to FIGURES 7A-7B;

10

[0027] FIGURE 8C illustrates a bond formed in accordance with one embodiment of the present invention; and

[0028] FIGURE 9 is a flowchart depicting functional steps employed in one embodiment of the present invention.

PROVISIONAL
PATENT
APPLICATION

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

A. Overview

[0029] In accordance with exemplary embodiments of the present invention, a method is provided for bonding and packaging components and members of Micro-Electro-Mechanical Systems (MEMS) and MEMS based products using a Solid-Liquid InterDiffusion (SLID) bonding process, a process not believed to have been previously contemplated in the MEMS and MEMS based technology field. For example, a MEMS product such as a ring-laser gyroscope, may be manufactured using a bonding and packaging process according to embodiments of the present invention. Additionally, devices such as micro-machines as well as devices fabricated using nano-technology or other electronic and mechanical processing methods, may be bonded and packaged in accordance with embodiments of the present invention. Furthermore, a description of a MEMS device fabricated in accordance with one embodiment of the present invention is provided.

B. A Microchip Package for MEMS based Products

[0030] Figure 1A is a side view of an illustration of packaging employed in accordance with one embodiment of the present invention. A chip 100 is provided as a housing for a micro-machine 110. The chip 100 includes a molded plastic package 102 comprising multiple pins 104a-b. A substrate 106 is present at the base of the chip 100 within the plastic package 102. A micro-machine chip 108 is coupled to the substrate 106 and to the micro-machine 110. A cover 114 is coupled to the micro-machine chip 108 using multiple bonds 116a-b. The cover 114 is coupled to the micro-machine chip 108 in a manner such that open space 112 remains between the cover 114 and the micro-machine 110. Leads 118a-b are present to electrically couple the micro-machine chip 108 to the pins 104a-b.

[0031] The chip 100 illustrated in Figure 1A may comprise more or fewer members than described. For instance, two pins 104a-b have been illustrated, although those skilled in the art will recognize that a chip may comprise no extruding pins or hundreds of pins. Additionally, 5 more or fewer members may be present in the chip 100 other than the substrate 106, the micro-machine chip 108, the micro-machine 110 and the cover 114. In one embodiment, the chip 100 comprises a MEMS with the micro-machine 110 illustrated in Figure 1A operable to perform electrical and mechanical operations. The cover 114 is preferably comprised of a material such as silicon, glass or a ceramic material. The cover 114 includes a cavity which allows open space 112 between the cover 114 and the micro-machine 110 providing components of the micro-machine 110 the ability to move freely. For example, a miniaturized valve may be movably coupled to the micro-machine 110 and the valve may open and close within the open space 112 provided. The micro-machine 110 may be any such electro-mechanical machine used in accordance with MEMS and MEMS based devices and may be comprised of a silicon substrate. 10 For instance, the micro-machine 110 may be a sensor for use in an air-bag system in an automobile.

[0032] Figure 1B is an expanded view of a portion of Figure 1A illustrating the bonds 116a-b between the cover 114 and the micro-machine chip 108 arranged in accordance with one 20 embodiment of the present invention. Multiple layers of material are illustrated composing the bonds 116a-b. More or fewer layers of material may be used in accordance with various embodiments of the present invention. In one embodiment, the cover 114, as illustrated in Figure 1A, is bonded to the micro-machine chip 108. In another embodiment, the cover 114 may be bonded directly to the substrate 106. In this second embodiment, the leads 118a-b pass

through the cover 114 to electrically couple the micro-machine chip 108 to the pins 104a-b. The cover 114 preferably fully covers the micro-machine 110.

[0033] Figure 2A is a cut open top view of the chip 100. The substrate 106 is shown mounted within a base of the chip 100 with the micro-machine chip 108 mounted upon the substrate 106. The micro-machine 110 is shown mounted upon the micro-machine chip 108. A portion of the cover 114 is illustrated as well. As illustrated in Figure 2A, the cover 114 fully covers the micro-machine 110 and the micro-machine chip 108. The cover 114 may only need to fully cover the micro-machine 110 to provide a hermetic seal for protection of the micro-machine 110. The chip 100 is illustrated with twelve pins 104a-l. Each pin 114a-l has a corresponding lead electrically coupling the pins 104a-l to the micro-machine chip 108. As shown in Figure 2A, pins 104a-f are illustrated with corresponding leads 118a-f. A chip may contain more or fewer pins than are illustrated within Figure 2A. Moreover, the cover 114 need not entirely cover the micro-machine 110 in some applications, such as gas-sensing applications.

[0034] Figure 2B is an expanded view of a portion of Figure 2A illustrating a bond between the micro-machine chip 108 and the substrate 106, and a bond between the micro-machine 110 and the micro-machine chip 108 arranged in accordance with one embodiment of the present invention. The bonds comprise multiple layers of materials shown as 132a, 144a, 140a and 138a, and 132b, 144b, 140b and 138b. More or fewer layers of materials may be used in the bonds than are illustrated. The bonds couple the micro-machine chip 108 to the substrate 106 and the micro-machine 110 to the micro-machine chip 108.

[0035] It will be understood, however, that the packaging employed in Figures 1A, 1B, 2A, and 2B are examples only, and embodiments of the present invention are not limited to such

plastic packaging options or to bonds comprising multiple layers. For example, in another embodiment, a Leadless Ceramic Chip Carrier (LCCC) package may be used as a housing for the micro-machine 110. In an exemplary embodiment, a ring-laser gyroscope MEM is manufactured using the bonds 116a-b shown in Figure 1B and an LCCC package (not illustrated). The LCCC package may be provided without external metallic pins, such as pins 104a-b illustrated in Figure 1A, but rather with a metallized castellation exposed on the underside of the LCCC package for electrical connections. The LCCC package may also use the bonds 116a-b illustrated in Figure 1B to seal the package around the ring laser gyroscope.

10 C. Preparation of Surfaces for Bonding Members to MEMS based Products

[0036] Figures 3A-3C are conceptual process diagrams showing stages of processing an upper mating surface 130 in accordance with one embodiment of the present invention. The processes illustrated in Figures 3A-3C illustrate a method of preparing the upper mating surface 130 in order to bond the upper mating surface 130 to another mating surface. Figure 3A illustrates the upper mating surface 130. The upper mating surface 130 may be a surface of the micro-machine 110, or a surface of the cover 114. A layer of an upper bonding material 132 is deposited on the upper mating surface 130. In a preferred embodiment, the upper bonding material 132 is a layer of chromium (Cr) having a thickness of about 20 Angstroms. The upper bonding material 132 may comprise a layer of chromium having a thickness between about 5 Angstroms to approximately 100 Angstroms. The upper bonding material 132 may also be a material having properties similar to those of chromium such as Group 6 elements.

[0037] In another embodiment, the upper bonding material 132 may be omitted. For instance, if the upper mating surface 130 comprises a metal or a ceramic mating surface, then the layer of

chromium may provide little or no benefit. The upper bonding material 132 is chosen to have preferred adhering properties to the upper mating surface 130 to allow a second bonding material to be deposited onto the upper bonding material 132, thereby allowing the second bonding material to be deposited onto the upper mating surface 130. The upper bonding material 132
5 more suitably bonds with selected mating surfaces than the resulting bond formed. Figure 3B illustrates the upper bonding material 132 deposited onto the upper mating surface 130.

[0038] A layer of an upper diffusion material 134 is then deposited onto the upper bonding material 132. In one embodiment, the upper diffusion material 134 is a layer of gold (Au) with a thickness of about 1 micron. In another embodiment, the upper diffusion material 134 is a layer of tin (Sn) with a thickness of about 1 micron. The upper diffusion material 134 may be as thin as about 100 Angstroms or as thick as about 63,500,000 Angstroms (i.e., 0.25 inches), according to embodiments of the present invention. Alternate materials that may be used for the upper diffusion material 134 are materials with similar properties to those of gold such as noble metals, inert metals, or elements selected from Groups 1B, 2B, and 3B of the periodic table of elements.
10 Figure 3C illustrates the upper mating surface 130 with the upper diffusion material 134 deposited upon the upper bonding material 132. An upper mating layer 135 comprises the upper mating surface 130, the upper bonding material 132 and the upper diffusion material 134. In an alternative embodiment, the upper mating layer 135 comprises only the upper mating surface 130
15 and the upper diffusion material 134.
20

[0039] Figures 4A-4C are conceptual process diagrams showing stages of one method of processing a lower mating surface 136 according to one embodiment of the present invention. Figures 4A-4C illustrate a process of preparing the lower mating surface 136 for bonding to

another surface. Figure 4A illustrates the lower mating surface 136. The lower mating surface 136 may be a surface of the substrate 106, or a surface of the micro-machine chip 108. A layer of a lower bonding material 138 is deposited on the lower mating surface 136. In a preferred embodiment, the lower bonding material 138 is a layer of chromium (Cr) having a thickness of 5 about 20 Angstroms. The lower bonding material 138 may comprise a layer of chromium having a thickness between about 5 Angstroms to approximately 100 Angstroms. Alternate materials that may be used for the lower bonding material 138 are materials having properties similar to those of chromium, such as elements of Group 6 of the periodic table of elements. In another embodiment, the lower bonding material 138 is omitted. For instance, if the lower mating surface 136 is a metal or a ceramic surface, then the layer of chromium can be omitted. Figure 4B illustrates the lower bonding material 138 deposited on the lower mating surface 136.

[0040] A layer of a lower diffusion material 140 is then deposited onto the lower bonding material 138. In one embodiment, the lower diffusion material 140 is a layer of gold (Au) having a thickness of about 1 micron. In another embodiment, the lower diffusion material 140 is a layer of tin (Sn) having a thickness of about 1 micron. The lower diffusion material 140 may comprise a layer of thickness between about 100 Angstroms to about 0.25 inches. Alternate materials that may be used for the lower diffusion material 140 are materials with similar properties to those of gold such as noble metals, inert metals, or elements selected from Groups 1B, 2B, and 3B. Figure 4C illustrates the lower diffusion material 140 deposited onto the lower bonding material 138. As illustrated in Figure 4C, a lower mating layer 141 comprises the lower mating surface 136, the lower bonding material 138 and the lower diffusion material 140.

[0041] The upper mating surface 130 and the lower mating surface 136 are interchangeable. In a preferred embodiment, the upper mating surface 130 is either a surface of the micro-machine 110 or a surface of the cover 114, as mentioned. However, the upper mating surface may also be a surface of the substrate 106, a surface of the micro-machine chip 108 or other surfaces of members of the chip 100. Likewise, the lower mating surface may comprise a surface of the micro-machine 110, a surface of the cover 114 or other surfaces of members of the chip 100. For example, additional elements may be bonded to an upper surface of the micro-machine 110 or the cover 114.

[0042] The processing illustrated in Figures 3A-3C and Figures 4A-4C prepares the lower mating surface 136 and the upper mating surface 130 to be bonded together. The processing of the upper mating surface 130 as shown in Figures 3A-3C and the processing of the lower mating surface 136 as shown in Figures 4A-4C may occur simultaneously or sequentially. In addition, cleaning and preparation of these surfaces may be necessary prior to the deposition of bonding materials, and prior to bonding these surfaces together. For example, the upper mating surface 130 and the lower mating surface 136 should be sufficiently clear of impurities to allow for an effective bond without defects to form between the upper and lower mating surfaces 130, 136.

[0043] Figure 5A illustrates a conceptual processing step employed in one embodiment of the present invention. Figure 5A illustrates one step of the preparation of the upper mating surface 130 and the lower mating surface 136 to be bonded together. An interdiffusion material 142 is deposited between the upper diffusion material 134 and the lower diffusion material 140. The interdiffusion material 142 may be deposited onto the lower diffusion material 140 or onto the upper diffusion material 134. In one embodiment, the interdiffusion material 142 is indium (In)

having a thickness between about 50 Angstroms to about 0.125 inches depending on the thickness of the lower and upper diffusion materials 140, 134. It may be desired to provide the lower and upper diffusion materials 140, 134 and the interdiffusion material 142 in a 2:1 ratio. In another embodiment, the interdiffusion material 142 is lead (Pb) having a thickness of about 5 50 Angstroms to about 0.125 inches. Additional interdiffusion materials may be used such as materials with similar properties to those of indium and lead.

[0044] Figure 5B illustrates a conceptual alloy bond 146 created in accordance with one embodiment of the present invention. The upper mating layer 135 is pressed against the lower mating layer 141 with the interdiffusion material 142 deposited between the two layers to create an alloy to serve as a bond. The upper mating layer 135 and the lower mating layer 141 are heated while being pressed together. The pressure, heat, and time of each applied during the bonding process depends upon the elements used within the bond. A preferred embodiment of the present invention will now be discussed in relation to an example.

10 15 D. Example: Bonding a Metal Base to a Glass Component in a MEMS Device

[0045] In one instance, a glass upper mating surface 130 may be bonded to a metal dielectric lower mating surface 136. Approximately, a 100 Angstrom layer of chromium is deposited on 20 the glass surface and on the metal surface. The chromium layers are the upper and lower bonding materials 132, 138 as illustrated in Figure 5A. Approximately, a one micron layer of gold is then deposited onto each of the chromium layers. The gold layers are the upper and lower diffusion materials 134, 140 as illustrated in Figure 5A. Approximately, a one micron indium layer is then deposited onto only one of the gold layers. The indium layer may be 25 deposited onto either gold layer. The indium layer is the interdiffusion material 142 as illustrated

in Figure 5A. The indium layer 142 thickness is half the thickness of the combination of the gold layers 134, 140 in accordance with the desired 2:1 ratio of the lower and upper diffusion materials 140, 134 and the interdiffusion material 142.

5 [0046] The glass and metal surfaces 130, 136 are then coupled together by pressing the glass surface 130, with the chromium and gold layers 132, 134 deposited on its surface, against the metal surface 136, with the chromium and gold layers 138, 140 deposited on its surface, with the indium layer 142 deposited between the two surfaces 130, 136 at a pressure of 2 Pounds per Square Inch (PSI), and at a temperature of 100° Celsius (C) for approximately 6 hours. The

10 layers of materials are heated to 100°C in order to stimulate a thermal diffusion process between the elements to allow for the elements to diffuse into one another. Upon applying the pressure, an alloy material 144 is created comprising the gold and indium elements as illustrated in Figure 5B. Using these specified amounts of pressure, heat, and time, theoretically a two or three time constant safety factor of the diffusion of the indium layer 142 into the gold layers 140, 134 will result. For instance, the diffusion of the indium layer 142 into the gold layers 140, 134 may be sufficiently complete after 1 hour using the specified temperatures and pressures, however after 6 hours, the diffusion can be assured to be complete. In this example, it may be necessary to have a two to one ratio of gold to indium in order to avoid a residual build-up of indium during the bonding process.

20 [0047] Within the example discussed above, a preferred pressure, temperature, and time of applying each are specified. However, alternate pressures, temperatures and times would also result in acceptable bonds and alloy materials 144. The time for applying the pressure and temperature is related to the rate of diffusion for the elements. For instance, increasing the

temperature from about 100°C to about 200°C would lower the diffusion time to approximately a few minutes because the indium layer 142 would diffuse more rapidly into the gold layers 134, 140. The rate of diffusing the indium layer 142 into the gold layers 134, 140 approximately doubles for every 10°C increase in temperature. Using higher temperatures relieves stress within 5 the bonding process. As mentioned, it may be necessary to provide alloys comprised of two micron layers of gold or tin bonded with a one micron layer of indium or lead in accordance with a 2:1 ratio of gold and tin to indium and lead to provide a suitable bond.

[0048] The time-temperature-pressure relationship used in the example bonding process may

10 be calculated using equation 1 (Eq. 1) provided below:

$$(Eq. 1) \quad D = D_0 * \exp(-Q/(RT))$$

Where: D is the diffusion rate
15 D_0 is the diffusion constant in units of cm^2/sec
Q is the activation energy in units of cal/mole
T is temperature in units of Kelvin
R is the Gas Constant; i.e., 1.98 cal/mole K

The diffusion constant (D_0) and activation energy (Q) are dependent upon the materials chosen for the bond. The diffusion constant and the activation energy of selected materials may be 20 found in a reference book such as "Chemical Rubber Company (CRC) Handbook of Chemistry and Physics," under section heading "Radioactive Tracer Diffusion Date for Pure Metals," pages F-46-F-52, the full disclosure of which is herein incorporated by reference. The following is a table of diffusion constants and activation energies from the CRC Handbook of representative materials for use in embodiments of the present invention:

Materials	Q (cal/mole)	$D_0 (\text{cm}^2/\text{sec})$
In diffused into Au	6700	0.009
Sn into Au	11000	0.0058
Zinc into Silver	27600	0.45
Pb into Copper	14440	0.046

Indium and gold may be preferred for use in the bonding process of embodiments of the present invention. The low activation energy and relatively high diffusion constant of indium diffusion into gold leads to a low temperature process that forms a high strength and high temperature bond.

[0049] The above equation (Eq. 1) may be used to calculate an effective temperature necessary to meet a desired diffusion rate that may be established due to manufacturing constraints and due to properties of selected materials. The pressure used in the bonding process may be primarily

10 used to place the upper mating surface 130 and the lower mating surface 136 into intimate contact with each other. Consequently, an effective pressure is needed to press and hold the upper and lower mating surfaces 130, 136 in contact with each other. For example, a pressure as low as that necessary to place the upper and lower mating surfaces into contact with each other may be used. Alternatively, a high pressure, such as a few thousand PSI, may be used which 15 may result in a stronger bond. The bonding process may be considered complete by using a one or two time constant safety factor. A bond strength may be tested by using a pull test. For instance, a pull test machine, such as an Instron® fatigue test machine, may be used to test the integrity of the bond.

20 [0050] The strength of the bond formed using the bonding process mentioned may be determined by the depth of diffusion of the indium layer 142 into the gold layers 134, 140. The depth of diffusion, x, can be estimated and calculated by using equation 2 (Eq. 2) provided below:

$$(Eq. 2) \quad x = \sqrt{D * t}$$

25 Where: x is the distance where 50% of diffusion has occurred in units of cm

sq() is square root of()
D is the diffusion rate in units of cm^2/sec
T is time in units of seconds

5 Within the example above, given a selected bonding temperature, such as about 20°C or about
300 Kelvin, and thickness of materials, such as about 0.01 cm depth of diffusion, the effective
time required to diffuse the indium layer 142 into the gold layers 134, 140 can be calculated as
follows:

10 (i) Obtain Q and D_0 from CRC Handbook for In diffusion into Au: $Q=6700 \text{ cal/mole}$
 $D_0=0.009 \text{ cm}^2/\text{sec}$

15 (ii) Calculate D from Eq 1: $D=0.009\exp(-6700/(1.98*300))=1.136\text{e-}07 \text{ cm}^2/\text{sec}$

15 (iii) Calculate time to diffuse 50%: $t=(x^2/D)=(0.0001/1.136\text{e-}07)=880.28 \text{ seconds}$

20 (iv) After approximately 900 seconds (i.e., 15 minutes), 50% of diffusion will have
occurred, then after 6 hours at least 99% of diffusion can be assumed to have
occurred

Increasing the temperature to about 130°C (i.e., about 400 Kelvin), increases the diffusion rate to
 $D=1.906\text{e-}06 \text{ cm}^2/\text{sec}$ and lowers the time to diffuse to $t=52.47 \text{ seconds}$ for 50% diffusion. The
time is related to the temperature used as shown in Eq. 2 above. An effective time for the
bonding process to conclude may be estimated after calculating the time necessary for 50%
diffusion. For instance, in the example above, after 15 minutes, 50% diffusion of the indium
layer 142 into the gold layers 134, 140 will have occurred. It can then be estimated and assumed
that after an effective time, such as 6 hours, approximately 99% diffusion will have occurred.
An effective time such as 1 hour may be sufficient for a suitable bond strength in other
applications.

25 [0051] In a preferred embodiment, the alloy material 144 is comprised of gold and indium. For
example, the resulting alloy material 144 may be AuIn_2 . Indium has a melting temperature of
156°C and gold has a melting temperature of 1064°C. Therefore, when selecting gold and
30 indium layer thickness, the gold layer should be of sufficient thickness to enable the indium layer

to substantially diffuse into the gold layer. The temperature chosen at which to bond the upper mating layer 135 to the lower mating layer 141 should raise the temperature of the area of contact between the upper and lower diffusion materials 134, 140 and the interdiffusion material 142 above the melting temperature of the eutectic binary alloy of the materials used while 5 pressing the upper mating layer 135 to the lower mating layer 141. For example, using gold for the upper and lower diffusion materials 134, 140 and using indium for the interdiffusion material 142, the melting temperature of an eutectic gold-indium alloy such as AuIn_2 , is about 495°C.

[0052] The alloy material 144 results from the upper and lower diffusion materials 134, 140 and the interdiffusion material 142. As illustrated in Figure 5B, part of the lower diffusion material 140 remains. Alternatively, a portion of the upper diffusion material 134 may remain. Likewise, portions of both the upper and lower diffusion materials 134, 140 may remain, or both of the upper and lower diffusion materials 134, 140 may be completely formed and consumed within the alloy material 144.

E. Bonding Members of MEMS based Products

[0053] Figure 6A illustrates a bonding process implemented in accordance with one embodiment of the present invention. Figure 6A is an expanded detailed conceptual view of the alloy bond 146. Within Figure 6A, and subsequently Figures 6B, 7A, 7B, 8A, and 8B, the upper 20 and lower diffusion materials 132, 140 are illustrated as gold, and the interdiffusion material 142 is illustrated as indium. The upper and lower diffusion materials 134, 140 are placed adjacent one another with the interdiffusion material 142 placed in between as illustrated within Figure 5A. In one embodiment, the amount of the gold layers 134, 140 is applied in excess of the

amount of the indium layer 142. For example, the thickness of the gold layers 134, 140 may be approximately twice the thickness of the indium layer 142, as mentioned.

[0054] Figure 6B conceptually illustrates a bonding process implemented in accordance with one embodiment of the present invention. The alloy material 144 forms between each gold layer 134, 140 and indium layer 142 upon pressing the gold layers 134, 140 and indium layer 142 against one another. Gold atoms diffuse into both sides of the indium layer 142 as shown by arrows in Figure 6A. Likewise, indium atoms diffuse into each of the gold layers 134, 140 as shown by arrows. The resulting intrinsic gold layers 134, 140 and indium layer 142 are thinner than the initial intrinsic gold layers 134, 140 and indium layer 142.

[0055] Figure 7A conceptually illustrates individual atoms of Figure 6A. Within Figure 7A, open squares represent gold atoms and solid black circles represent indium atoms. Initially, upon being placed adjacent one another, the gold layers 134, 140 and indium layer 142 are separate from one another and likewise the gold and indium atoms are separate as well. No mixture of atoms may be present at interfaces between the gold layers 134, 140 and indium layer 142. The gold and indium atoms are illustrated arranged in a lattice structure. For example, the indium atoms may be arranged in a tetragonal lattice structure and the gold atoms may be arranged in a Cubic Close-Packed (CCP) lattice structure.

[0056] Figure 7B illustrates diffusion of the individual atoms of Figure 7A according to the process illustrated in Figure 6B. Several indium and gold atoms diffuse throughout the gold layers 134, 140 and indium layer 142. Atoms of the gold layers 134, 140 may diffuse into the indium layer 142 and occupy interstitial lattice site positions of the indium layer 142, or gold atoms may occupy vacant lattice site positions of the indium layer 142. Vacant lattice site

positions arise from the indium atoms diffusing into the gold layers 134, 140. Likewise, indium atoms may diffuse into the gold layers 134, 140 and occupy interstitial lattice site positions or vacant lattice site positions.

5 [0057] The diffusion begins by applying a specified pressure and temperature to the gold layers 134, 140 and indium layer 142. The alloy material 144 will begin to form between each gold layer 134, 140 and the indium layer 142. The alloy material 144 couples the upper mating surface 130 to the lower mating surface 136. The alloy material 144 bond strength depends upon the amount of diffusion of the indium layer 142 into each of the gold layers 134, 140. A complete diffusion of the indium layer 142 would result in a strong alloy material 144 bond.

10 [0058] Figures 8A-8B illustrate amounts of concentrations of materials present according to Figures 7A-7B. Figure 8A illustrates an initial concentration versus position diagram according to Figure 7A. The concentrations are shown according to the amount of intrinsic material, and the positions are shown according to width of the materials. Initially, the gold layers 134, 140 and indium layer 142 comprise 100% of their intrinsic composition. The interface between each layer comprises an abrupt difference in concentrations of material.

15 [0059] Figure 8B illustrates an intermediate concentration versus position diagram according to Figure 7B. While performing the process illustrated in Figure 5B, the intermediate concentrations of the gold layers 134, 140, the indium layer 142, and the alloy material 144 are as shown in Figure 8B. The interface between each layer comprises a gradual transition of concentration from gold to indium. Centers of each interface between the gold layers 134, 140 and indium layer 142 are illustrated at points x_1 and x_2 . The center of each interface comprise 20 the alloy material 144 as illustrated in Figure 8B.

[0060] Figure 8C illustrates a conceptual final concentration of a bond formed in one embodiment of the present invention. In a homogeneous alloy bond 146, the center of the bond comprises approximately 66% concentration of gold and approximately 33% concentration of indium resulting in a homogeneous alloy material 144 as illustrated in the diagram of Figure 8C. This is consistent with a 2:1 ratio of gold to indium in accordance with embodiments of the present invention.

[0061] In one embodiment, the upper bonding material 132 includes properties that exhibit better bonding characteristics to the materials it is adjacent to, than the adjacent materials would have to each other. For instance, in the example discussed above, gold does not bond well to substances such as dielectrics, however chromium bonds well to dielectrics. Therefore, a layer of chromium is deposited onto the surface of the dielectric, and subsequently, the layers of gold and indium may be deposited upon the layer of chromium. The layer of chromium is necessary in this instance to achieve an acceptable adhesion contact.

[0062] The upper bonding material 132 and the lower bonding material 138 may be chosen to have higher melting temperatures than the upper and lower diffusion materials 134, 140 and the interdiffusion material 142. For example, in a preferred embodiment, chromium is chosen as the upper and lower bonding materials 132, 138. Chromium has a melting temperature of 1907°C, much larger than the melting temperatures of other preferred materials for use in accordance with embodiments of the present invention, such as gold 1064°C, lead 327°C, tin 450°C, and indium 156°C. Therefore, the bonding process in various embodiments of the present invention will not interfere with the bond between the chromium layer and its mating surfaces.

[0063] The pressure, heat, time of each applied, and other variables depend on the materials used in the layers of the bonds and the thickness of each because the diffusion rates for each material are different. Therefore, bond formation depends upon bonding temperature, mutual diffusivities, and diffusion rates of the diffusing materials. Within the alloy material 144,

5 nucleations and associated voids can form due to unequal diffusivities, dissimilar diffusion paths, and improper pressure, heat, and the extent of applying each to the bonding materials.

Nucleations and voids are not preferred because they can damage and weaken a bond. The associated variables used in the bonding process should therefore be chosen to provide a homogenous bond.

10 [0064] Accordingly, the pressure, heat and time applied may be calculated to achieve an ample amount of diffusion to obtain an acceptable bond strength. Due to various molecular sizes, various molecular shapes, and various binding of molecules, bond strengths and bond 15 homogeneity for materials are unequal. Diffusing rates, diffusivities and associated diffusion coefficients are obtained as a product of thermodynamic and kinetic factors and can be established from experimental studies and results as in the CRC Handbook mentioned earlier.

[0065] In one embodiment, a Solid to Liquid InterDiffusion (SLID) process is used to couple

the upper mating surface 130 to the lower mating surface 136. For a more complete

20 understanding of SLID bonding techniques, reference is made to: "Applications of Solid Liquid

Inter Diffusion (SLID) bonding integrated-circuit applications", by L. Bernstein et al.,

Transaction of the Metallurgical Society, vol. 236, Mar 1966, pp. 405-412. Furthermore, U.S.

Patent No. 5,106,009 to Humpston et al. is hereby incorporated by reference as describing

several possible SLID alloys and the suggested processing conditions for those alloys. The SLID

process is a solid state bonding operation where the bonding temperatures do not exceed the melting points of the materials to be joined, and therefore, the formation of a bond is based on a chemical diffusion of atoms of materials across their adjacent interfaces. The SLID process is a low temperature process that yields a high temperature and high strength bond.

5 [0066] The bonding method may also affect the operating range of the micro-machine 110 and MEMS, depending on the conditions under which the selected bonding materials degrade. As a result, melting temperatures of materials may limit possible applications of MEMS. For example, using the preferred materials, the limiting melting temperature of the bond formed will

10 be due to the indium material, although using the SLID process the melting temperature of the bond will be higher than that of indium. For instance, the melting temperature of indium is 156°C, however, when formed with gold, the resulting alloy material 144 melting temperature is between 232°-450°C. Accordingly, as an example, the highest operating temperature for a MEMS including an AuIn₂ bond may be near 450°C.

15 [0067] The bonding process disclosed in accordance with embodiments of the present invention allows a bond to be formed with a higher melting temperature than the element contained within the bond with the lowest intrinsic melting temperature. The materials used within the bond should be chosen according to an intended application of the MEMS. In 20 addition, the chemical compatibility of materials should be taken into account when choosing materials for use in the bonds. Moreover, the bonding process should not interfere with previously completed processing steps nor limit subsequent processing steps.

F. Bonding and Packaging Processes used in accordance with Applications of

25 MEMS based Products

10 [0068] In one embodiment, an application of a MEMS device is miniaturizing sensors and electronics. For example, a ten cubic inch system may be modified into a two cubic inch system by use of wafer scale integration in accordance with a MEMS device. In one embodiment, wafer scale integration is a process that slices large crystals of pure silicon into thin wafers of silicon.

5 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130 135 140 145 150 155 160 165 170 175 180 185 190 195 200 205 210 215 220 225 230 235 240 245 250 255 260 265 270 275 280 285 290 295 300 305 310 315 320 325 330 335 340 345 350 355 360 365 370 375 380 385 390 395 400 405 410 415 420 425 430 435 440 445 450 455 460 465 470 475 480 485 490 495 500 505 510 515 520 525 530 535 540 545 550 555 560 565 570 575 580 585 590 595 600 605 610 615 620 625 630 635 640 645 650 655 660 665 670 675 680 685 690 695 700 705 710 715 720 725 730 735 740 745 750 755 760 765 770 775 780 785 790 795 800 805 810 815 820 825 830 835 840 845 850 855 860 865 870 875 880 885 890 895 900 905 910 915 920 925 930 935 940 945 950 955 960 965 970 975 980 985 990 995 1000 1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055 1060 1065 1070 1075 1080 1085 1090 1095 1100 1105 1110 1115 1120 1125 1130 1135 1140 1145 1150 1155 1160 1165 1170 1175 1180 1185 1190 1195 1200 1205 1210 1215 1220 1225 1230 1235 1240 1245 1250 1255 1260 1265 1270 1275 1280 1285 1290 1295 1300 1305 1310 1315 1320 1325 1330 1335 1340 1345 1350 1355 1360 1365 1370 1375 1380 1385 1390 1395 1400 1405 1410 1415 1420 1425 1430 1435 1440 1445 1450 1455 1460 1465 1470 1475 1480 1485 1490 1495 1500 1505 1510 1515 1520 1525 1530 1535 1540 1545 1550 1555 1560 1565 1570 1575 1580 1585 1590 1595 1600 1605 1610 1615 1620 1625 1630 1635 1640 1645 1650 1655 1660 1665 1670 1675 1680 1685 1690 1695 1700 1705 1710 1715 1720 1725 1730 1735 1740 1745 1750 1755 1760 1765 1770 1775 1780 1785 1790 1795 1800 1805 1810 1815 1820 1825 1830 1835 1840 1845 1850 1855 1860 1865 1870 1875 1880 1885 1890 1895 1900 1905 1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046 2048 2050 2052 2054 2056 2058 2060 2062 2064 2066 2068 2070 2072 2074 2076 2078 2080 2082 2084 2086 2088 2090 2092 2094 2096 2098 2100 2102 2104 2106 2108 2110 2112 2114 2116 2118 2120 2122 2124 2126 2128 2130 2132 2134 2136 2138 2140 2142 2144 2146 2148 2150 2152 2154 2156 2158 2160 2162 2164 2166 2168 2170 2172 2174 2176 2178 2180 2182 2184 2186 2188 2190 2192 2194 2196 2198 2200 2202 2204 2206 2208 2210 2212 2214 2216 2218 2220 2222 2224 2226 2228 2230 2232 2234 2236 2238 2240 2242 2244 2246 2248 2250 2252 2254 2256 2258 2260 2262 2264 2266 2268 2270 2272 2274 2276 2278 2280 2282 2284 2286 2288 2290 2292 2294 2296 2298 2300 2302 2304 2306 2308 2310 2312 2314 2316 2318 2320 2322 2324 2326 2328 2330 2332 2334 2336 2338 2340 2342 2344 2346 2348 2350 2352 2354 2356 2358 2360 2362 2364 2366 2368 2370 2372 2374 2376 2378 2380 2382 2384 2386 2388 2390 2392 2394 2396 2398 2400 2402 2404 2406 2408 2410 2412 2414 2416 2418 2420 2422 2424 2426 2428 2430 2432 2434 2436 2438 2440 2442 2444 2446 2448 2450 2452 2454 2456 2458 2460 2462 2464 2466 2468 2470 2472 2474 2476 2478 2480 2482 2484 2486 2488 2490 2492 2494 2496 2498 2500 2502 2504 2506 2508 2510 2512 2514 2516 2518 2520 2522 2524 2526 2528 2530 2532 2534 2536 2538 2540 2542 2544 2546 2548 2550 2552 2554 2556 2558 2560 2562 2564 2566 2568 2570 2572 2574 2576 2578 2580 2582 2584 2586 2588 2590 2592 2594 2596 2598 2600 2602 2604 2606 2608 2610 2612 2614 2616 2618 2620 2622 2624 2626 2628 2630 2632 2634 2636 2638 2640 2642 2644 2646 2648 2650 2652 2654 2656 2658 2660 2662 2664 2666 2668 2670 2672 2674 2676 2678 2680 2682 2684 2686 2688 2690 2692 2694 2696 2698 2700 2702 2704 2706 2708 2710 2712 2714 2716 2718 2720 2722 2724 2726 2728 2730 2732 2734 2736 2738 2740 2742 2744 2746 2748 2750 2752 2754 2756 2758 2760 2762 2764 2766 2768 2770 2772 2774 2776 2778 2780 2782 2784 2786 2788 2790 2792 2794 2796 2798 2800 2802 2804 2806 2808 2810 2812 2814 2816 2818 2820 2822 2824 2826 2828 2830 2832 2834 2836 2838 2840 2842 2844 2846 2848 2850 2852 2854 2856 2858 2860 2862 2864 2866 2868 2870 2872 2874 2876 2878 2880 2882 2884 2886 2888 2890 2892 2894 2896 2898 2900 2902 2904 2906 2908 2910 2912 2914 2916 2918 2920 2922 2924 2926 2928 2930 2932 2934 2936 2938 2940 2942 2944 2946 2948 2950 2952 2954 2956 2958 2960 2962 2964 2966 2968 2970 2972 2974 2976 2978 2980 2982 2984 2986 2988 2990 2992 2994 2996 2998 2999 3000 3001 3002 3003 3004 3005 3006 3007 3008 3009 3010 3011 3012 3013 3014 3015 3016 3017 3018 3019 3020 3021 3022 3023 3024 3025 3026 3027 3028 3029 3030 3031 3032 3033 3034 3035 3036 3037 3038 3039 3040 3041 3042 3043 3044 3045 3046 3047 3048 3049 3050 3051 3052 3053 3054 3055 3056 3057 3058 3059 3060 3061 3062 3063 3064 3065 3066 3067 3068 3069 3070 3071 3072 3073 3074 3075 3076 3077 3078 3079 3080 3081 3082 3083 3084 3085 3086 3087 3088 3089 3090 3091 3092 3093 3094 3095 3096 3097 3098 3099 3100 3101 3102 3103 3104 3105 3106 3107 3108 3109 3110 3111 3112 3113 3114 3115 3116 3117 3118 3119 3120 3121 3122 3123 3124 3125 3126 3127 3128 3129 3130 3131 3132 3133 3134 3135 3136 3137 3138 3139 3140 3141 3142 3143 3144 3145 3146 3147 3148 3149 3150 3151 3152 3153 3154 3155 3156 3157 3158 3159 3160 3161 3162 3163 3164 3165 3166 3167 3168 3169 3170 3171 3172 3173 3174 3175 3176 3177 3178 3179 3180 3181 3182 3183 3184 3185 3186 3187 3188 3189 3190 3191 3192 3193 3194 3195 3196 3197 3198 3199 3200 3201 3202 3203 3204 3205 3206 3207 3208 3209 3210 3211 3212 3213 3214 3215 3216 3217 3218 3219 3220 3221 3222 3223 3224 3225 3226 3227 3228 3229 3230 3231 3232 3233 3234 3235 3236 3237 3238 3239 3240 3241 3242 3243 3244 3245 3246 3247 3248 3249 3250 3251 3252 3253 3254 3255 3256 3257 3258 3259 3260 3261 3262 3263 3264 3265 3266 3267 3268 3269 3270 3271 3272 3273 3274 3275 3276 3277 3278 3279 3280 3281 3282 3283 3284 3285 3286 3287 3288 3289 3290 3291 3292 3293 3294 3295 3296 3297 3298 3299 3299 3300 3301 3302 3303 3304 3305 3306 3307 3308 3309 3310 3311 3312 3313 3314 3315 3316 3317 3318 3319 3320 3321 3322 3323 3324 3325 3326 3327 3328 3329 3329 3330 3331 3332 3333 3334 3335 3336 3337 3338 3339 3339 3340 3341 3342 3343 3344 3345 3346 3347 3348 3349 3349 3350 3351 3352 3353 3354 3355 3356 3357 3358 3359 3359 3360 3361 3362 3363 3364 3365 3366 3367 3368 3369 3369 3370 3371 3372 3373 3374 3375 3376 3377 3378 3379 3379 3380 3381 3382 3383 3384 3385 3386 3387 3388 3389 3389 3390 3391 3392 3393 3394 3395 3396 3397 3398 3399 3399 3400 3401 3402 3403 3404 3405 3406 3407 3408 3409 3409 3410 3411 3412 3413 3414 3415 3416 3417 3418 3419 3419 3420 3421 3422 3423 3424 3425 3426 3427 3428 3428 3429 3430 3431 3432 3433 3434 3435 3436 3437 3438 3439 3439 3440 3441 3442 3443 3444 3445 3446 3447 3448 3449 3449 3450 3451 3452 3453 3454 3455 3456 3457 3458 3459 3459 3460 3461 3462 3463 3464 3465 3466 3467 3468 3469 3469 3470 3471 3472 3473 3474 3475 3476 3477 3478 3479 3479 3480 3481 3482 3483 3484 3485 3486 3487 3488 3489 3489 3490 3491 3492 3493 3494 3495 3496 3497 3498 3499 3499 3500 3501 3502 3503 3504 3505 3506 3507 3508 3509 3509 3510 3511 3512 3513 3514 3515 3516 3517 3518 3519 3519 3520 3521 3522 3523 3524 3525 3526 3527 3528 3528 3529 3530 3531 3532 3533 3534 3535 3536 3537 3538 3539 3539 3540 3541 3542 3543 3544 3545 3546 3547 3548 3549 3549 3550 3551 3552 3553 3554 3555 3556 3557 3558 3559 3559 3560 3561 3562 3563 3564 3565 3566 3567 3568 3569 3569 3570 3571 3572 3573 3574 3575 3576 3577 3578 3579 3579 3580 3581 3582 3583 3584 3585 3586 3587 3588 3589 3589 3590 3591 3592 3593 3594 3595 3596 3597 3598 3599 3599 3600 3601 3602 3603 3604 3605 3606 3607 3608 3609 3609 3610 3611 3612 3613 3614 3615 3616 3617 3618 3619 3619 3620 3621 3622 3623 3624 3625 3626 3627 3628 3628 3629 3630 3631 3632 3633 3634 3635 3636 3637 3638 3639 3639 3640 3641 3642 3643 3644 3645 3646 3647 3648 3649 3649 3650 3651 3652 3653 3654 3655 3656 3657 3658 3659 3659 3660 3661 3662 3663 3664 3665 3666 3667 3668 3669 3669 3670 3671 3672 3673 3674 3675 3676 3677 3678 3679 3679 3680 3681 3682 3683 3684 3685 3686 3687 3688 3689 3689 3690 3691 3692 3693 3694 3695 3696 3697 3698 3699 3699 3700 3701 3702 3703 3704 3705 3706 3707 3708 3709 3709 3710 3711 3712 3713 3714 3715 3716 3717 3718 3719 3719 3720 3721 3722 3723 3724 3725 3726 3727 3728 3728 3729 3730 3731 3732 3733 3734 3735 3736 3737 3738 3739 3739 3740 3741 3742 3743 3744 3745 3746 3747 3748 3749 3749 3750 3751 3752 3753 3754 3755 3756 3757 3758 3759 3759 3760 3761 3762 3763 3764 3765 3766 3767 3768 3769 3769 3770 3771 3772 3773 3774 3775 3776 3777 3778 3779 3779 3780 3781 3782 3783 3784 3785 3786 3787 3788 3789 3789 3790 3791 3792 3793 3794 3795 3796 3797 3798 3799 3799 3800 3801 3802 3803 3804 3805 3806 3807 3808 3809 3809 3810 3811 3812 3813 3814 3815 3816 3817 3818 3819 3819 3820 3821 3822 3823 3824 3825 3826 3827 3828 3828 3829 3830 3831 3832 3833 3834 3835 3836 3837 3838 3839 3839 3840 3841 3842 3843 3844 3845 3846 3847 3848 3849 3849 3850 3851 3852 3853 3854 3855 3856 3857 3858 3859 3859 3860 3861 3862 3863 3864 3865 3866 3867 3868 3869 3869 3870 3871 3872 3873 3874 3875 3876 3877 3878 3879 3879 3880 3881 3882 3883 3884 3885 3886 3887 3888 3889 3889 3890 3891 3892 3893 3894 3895 3896 3897 3898 3899 3899 3900 3901 3902 3903 3904 3905 3906 3907 3908 3909 3909 3910 3911 3912 3913 3914 3915 3916 3917 3918 3919 3919 3920 3921 3922 3923 3924 3925 3926 3927 3928 3928 3929 3930 3931 3932 3933 3934 3935 3936 3937 3938 3939 3939 3940 3941 3942 3943 3944 3945 3946 3947 3948 3949 3949 3950 3951 3952 3953 3954 3955 3956 3957 3958 3959 3959 3960 3961 3962 3963 3964 3965 3966 3967 3968 3969 3969 3970 3971 3972 3973 3974 3975 3976 3977 3978 3979 3979 3980 3981 3982 3983 3984 3985 3986 3987 3988 3989 3989 3990 3991 3992 3993 3994 3995 3996 3997 3998 3999 3999 4000 4001 4002 4003 4004 4005 4006 4007 4008 4009 4009 4010 4011 4012 4013 4014 4015 4016 4017 4018 4019 4019 4020 4021 4022 4023 4024 4025 4026 4027 4028 4028 4029 4030 4031 4032 4033 4034 4035 4036 4037 4038 4039 4039 4040 4041 4042 4043 4044 4045 4046 4047 4048 4049 4049 4050 4051 4052 4053 4054 4055 4056 4057 4058 4059 4059 4060 4061 4062 4063 4064 4065 4066 4067 4068 4069 4069 4070 4071 4072 4073 4074 4075 4076 4077 4078 4079 4079 4080 4081 4082 4083 4084 4085 4086 4087 4088 4089 4089 4090 4091 4092 4093 4094 4095 4096 4097 4098 4099 4099 4100 4101 4102 4103 4104 4105 4106 4107 4108 4109 4109 4110 4111 4112 4113 4114 4115 4116 4117 4118 4119 4119 4120 4121 4122 4123 4124 4125 4126 4127 4128 4129 4129 4130 4131 4132 4133 4134 4135 4136 4137 4138 4139 4139 4140 4141 4142 4143 4144 4145 4146 4147 4148 4149 4149 4150 4151 4152 4153 4154 4155 4156 4157 4158 4159 4159 4160 4161 4162 4163 4164 4165 4166 4167 4168 4169 4169 4170 4171 4172 4173 4174 4175 4176 4177 4178 4179 4179 4180 4181 4182 4183 4184 4185 4186 4187 4188 4189 4189 4190 4191 4192 4193 4194 4195 4196 4197 4198 4199 4199 4200 4201 4202 4203 4204 4205 4206 4207 4208 4209 4209 4210 4211 4212 4213 4214 4215 4216 4217 4218 4219 4219 4220 4221 4222 4223 4224 4225 4226 4227 4228 4229 4229 4230 4231 4232 4233 4234 4235 4236 4237 4238 4239 4239 4240 4241 4242 4243 4244 4245 4246 4247 4248 4249 4249 4250 4251 4252 4253 4254 4255 4256 4257 4258 4259 4259 4260 4261 4262 4263 4264 4265 4266 4267 4268 4269 4269 4270 4271 4272 4273 4274 4275 4276 4277 4278 4279 4279 4280 4281 4282 4283 4284 4285 4286 4287 4288 4289 4289 4290 4291 4292 4293 4294 4

effective bond than a conventional tin-lead solder. The gold-indium SLID bond may be fabricated with less effort than a gold-tin SLID bond due to the conditions according to temperatures and pressures needed to fabricate each. However, tin may be preferred in more instances than indium for high quality vacuum systems because indium may be more

5 troublesome to control.

[0071] Figure 9 is a flowchart depicting a bonding process 160 employed in one embodiment of the present invention. In one embodiment, the bonding process 160 illustrates steps of manufacturing a MEMS or a MEMS based device, such as the chip 100 illustrated in Figure 1A.

10 The bonding process 160 begins by depositing layers of chromium and gold onto a surface of the micro-machine chip 108 as shown at block 162. The layer of chromium is deposited first, followed by the layer of gold. Next layers of chromium and gold are deposited on a surface of the micro-machine 110 as shown at block 164. As before, the layer of chromium is deposited first, followed by the layer of gold. Next, a layer of indium is deposited between the micro-machine chip 108 and the micro-machine 110 as shown at block 165. The layer of indium may be deposited onto the layer of gold on the micro-machine 110 or onto the layer of gold on the micro-machine chip 108. A bond is formed between the micro-machine 110 and the micro-machine chip 108 by pressing the layers of chromium and gold on the micro-machine chip 108 to the layers of chromium and gold on the micro-machine 110 with the layer of indium in between

15 20 in order to form a gold-indium alloy to serve as the bond as shown within block 166. While pressing the micro-machine chip 108 to the micro-machine 110, both the micro-machine chip 108 and the micro-machine 110 may be heated in order to stimulate a thermal diffusion of the layers of materials.

[0072] Subsequently, the cover 114 is coupled to the micro-machine chip 108 using the following process. Layers of chromium and gold are deposited onto a surface of the micro-machine chip 108 as shown at block 168. Next, layers of chromium and gold are deposited on a surface of the cover 114 as shown at block 170. As before while bonding the micro-machine chip 108 to the micro-machine 110, the layers of chromium are deposited first, followed by the layers of gold. Next, a layer of indium is deposited between the micro-machine chip 108 and the cover 114 as shown at block 171. The indium may be deposited onto either the gold layer on the micro-machine chip 108 or onto the gold layer on the cover 114. A bond is formed between the cover 114 and the micro-machine chip 108 by pressing the layers of chromium and gold on the micro-machine chip 108 to the layers of chromium and gold on the cover 114 with the layer of indium in between to form a gold-indium alloy to serve as the bond as shown at block 172.

[0073] Subsequently, the bonded materials are enclosed in a package as shown at block 174, such as the plastic package 102 illustrated within Figure 1A, a Small Outline Integrated Circuit (SOIC) package, a Plastic Leaded Chip Carrier (PLCC) package or a Quad Flat Package (QFP) that can all be adapted to meet a height requirement of the micro-machine 110 with a silicon cover 114 (e.g., usually 3 mm or above). The process of depositing chromium onto the micro-machine chip 108, the micro-machine 110, and the cover 114 may be omitted in some embodiments, especially if these members comprise a metal or ceramic material. In addition, alternate materials other than chromium, gold, and indium may be used in the bonding process 160 of the flowchart of Figure 9.

[0074] Another packaging option other than the plastic package 102 that may be used in accordance with block 174 is a matrix format package, comprised of a ceramic or a laminate

substrate. A cavity can be formed by placing an epoxy or adhesive dam around the bonded materials with the ceramic or laminate substrate mounted on top of the epoxy dam. The dam is applied after leads, such as leads 118a-f, are bonded to the micro-machine chip 108. The package can be lidded with a plastic, an aluminum or a ceramic material. The lid material can be 5 positioned over the epoxy or adhesive dam.

[0075] Still another packaging option that may be used in accordance with block 174 is a liquid encapsulant package. The liquid encapsulant packaging option may be used for fragile micro-machines because the liquid encapsulant packaging may be able to more sufficiently protect the 10 micro-machine 110 and the bonded materials than the plastic package 102 or the epoxy dam. A casing may be bonded to the surface of the micro-machine 110 and filled with liquid to create the liquid encapsulant. U.S. Patent No. 5,399,805 to Tyler et al. is hereby incorporated by reference as describing a possible liquid electronic packaging encapsulant. The bonding process 160 disclosed in accordance with embodiments of the present invention may be used with the 15 packaging techniques described within Tyler et al.

[0076] The deposition of layers of materials used in accordance with embodiments of the present invention and described within the flowchart of Figure 9 may be done using vacuum deposition. Such vacuum deposition methods as an electron beam vacuum deposition process, a 20 sputtering process, a Chemical Vapor Deposition (CVD) process, a Metal Organic Chemical Vapor Deposition (MOCVD) process, an ion beam process or the like, are all possible processes for forming layers of materials. The process used should produce substantially homogeneous layers free of defects to produce an effective bond. Each method of applying the materials to the 25 mating surfaces alters the physical condition of the mating surfaces differently. For example, an

electroplating process may introduce pores into the surfaces of the gold and indium materials.

Alternatively, a vacuum deposition process may produce more dense materials on the surfaces of mating surfaces. Correspondingly, the process of deposition of layers of materials should be chosen according to a desired application of the MEMS.

5 [0077] One of skill in the art will appreciate that the bonding and packaging processes discussed in accordance with embodiments of the present invention are believed to be capable of handling a mass production of MEMS. The bonding process 160 illustrated in the flowchart of Figure 9 may be used in practically all bonds necessary within a MEMS. Applying SLID

10 bonding to MEMS and MEMS based devices allows manufacturing and designing to be completed in a timely fashion and at a low cost.

[0078] Exemplary embodiments of the present invention have been illustrated and described.

15 It will be understood, however, that changes and modifications may be made to the present invention without deviating from the scope or extent of the present invention, as defined by the following claims. It should be understood that the processes, methods and devices described herein are not affiliated, related or limited to any particular type of system unless indicated otherwise.

20 [0079] In view of the wide variety of embodiments to which the principles of the present invention can be applied, it should be understood that the illustrated embodiments are exemplary only, and should not be taken as limiting the scope or extent of the present invention. For example, while gold, tin, chromium, lead, and indium have been described as preferred materials for use with the present invention, other materials and alloys may be used as well if bonding 25 process characteristics are chosen which are suitable for the selected bonding materials.

Additionally, more components or members of MEMS may be present other than those illustrated within the chip 100 of Figure 1A. For example, additional protective covers, non-conductive materials, and adhesive substances may be used in accordance with the chip 100 of Figure 1A. Moreover, the steps of the flowchart diagram in Figure 9 may be taken in sequences or steps other than those described, and more or fewer steps may be used in conjunction with bonding process 160.

[0080] The claims should not be read as limited to the described order or elements unless stated to that effect. Therefore, all embodiments that come within the scope and spirit of the following claims and equivalents thereto are claimed as the invention.

10
20200824000000